A Compact Extreme Scattering Event Cloud Towards AO 0235+164

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ABSTRACT

We present observations of a rare, rapid, high amplitude Extreme Scattering Event toward the compact BL-Lac AO 0235+164 at 6.65 GHz. The ESE cloud is compact; we estimate its diameter between 0.09 and 0.9 AU, and is at a distance of less than 3.6 kpc. Limits on the angular extent of the ESE cloud imply a minimum cloud electron density of $\sim 4 \times 10^3 \, cm^{-3}$. Based on the amplitude and timescale of the ESE observed here, we suggest that at least one of the transients reported by Bower et al. (2007) may be attributed to ESEs.

Subject headings: ISM: structure — BL Lacertae objects: individual (AO0235+164) — galaxies: active

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1.   Introduction

The $z = 0.940$ (Cohen et al., 1987) flat spectrum BL Lac AO 0235+164 has been known to exhibit variability since its discovery (MacLeod et al., 1976) over a broad range of wavelengths and timescales (Raiteri et al. (2006) and references therein). Two absorbing galaxy complexes exist along the line of sight to this source at $z = 0.524$ and $z = 0.851$ (Burbidge et al., 1976; Rieke et al., 1976), hindering interpretation of the spectrum and possibly contributing to the observed variability (e.g. by microlensing by stars in the foreground system (Ostriker & Vietri, 1985)). The source is amongst the most compact radio AGN: it exhibits long-term variability down to meter-wavelengths and is slightly resolved by high angular resolution VLBI at 43 GHz (Frey et al., 2000; Piner et al., 2006).

The extreme compactness of this source renders the interpretation of its variability difficult. For instance, there is debate whether the origin of the centimeter-wavelength intra-day variability in observed AO 0235+164 is primarily intrinsic or due to interstellar scintillation (ISS) (Kraus et al., 1999; Lovell et al., 2003), and on what timescales each contributes. In addition, the source compactness renders it highly susceptible to flux density deviations by the compact intervening refracting structures in the local ISM that give rise to Extreme Scattering Events (ESEs) (Fiedler et al., 1987) because it is easy for even a small cloud to subtend the angular extent of such a small source.

Of the three main causes of cm-wavelength variability, ESEs are the most rare and certainly the least understood. Almost all flat-spectrum AGN show variability (Altschuler & Wardle, 1977). The MASIV survey found that $\sim 20\%$ of this population exhibits scintillation at any one time with over 56% exhibiting ISS at any stage over the course of a year (Lovell et al., 2007; Jauncey et al., 2007). However, the estimated rate of ESE events in compact AGN is only $0.013 \, \mathrm{source}^{-1}\mathrm{yr}^{-1}$ (Fiedler et al., 1987)

There are various plausible interpretations as to the origins of the structures that give rise to ESEs. These include intrinsically turbulent ionized clouds, purely refractive (gaussian) lenses, and primarily neutral clouds enveloped by a thin ionized sheath that responsible for the cloud's refractive properties (Fiedler et al., 1994; Romani et al., 1987; Clegg et al., 1998; Walker & Wardle, 1998). These models pose a number of challenges; the electron densities implied by the plasma lens models requires the clouds to be $\sim 10^3$ times overpressured with respect to the ambient ISM, while the neutral-cloud interpretation implies that such structures would contain a large fraction of the baryonic dark matter content of the Milky Way.

In this paper we report an unusually short-timescale ESE in AO 0235+164. Our observations are reported in section 2, while in section 3 we show that both intrinsic variability

and interstellar scintillation are incapable of explaining this event, and discuss the physical properties of the ESE necessary to give rise to the observed lightcurve. Our conclusions are presented in section 4.

2. Observations

AO 0235+164 has been monitored quasi-continuously since 2003 as part of the Continuous Single-dish Monitoring of Intraday variability at Ceduna (COSMIC) program (McCulloch et al., 2005). The observations were conducted with the University of Tasmania Ceduna 30-m antenna at a center frequency of 6.65 GHz with a 300 MHz bandwidth. The flux density was sampled by scanning across the source in forward and reverse directions in both Right Ascension and Declination. The flux density measurements are obtained from the height of the gaussian profile of the source signal above the system temperature baseline. All the scans are scaled to a noise diode, which in turn is calibrated against 3C 227, which at this frequency has a flux density of 1.99 Jy (Baars et al., 1977). Measured pointing offsets are used to correct the amplitude in orthogonal scans to minimise the impact of inaccurate pointing on the measured amplitude. A correction is made to account for gain dependence of the antenna due to the distortion with respect to elevation. The four fitted amplitudes are averaged together to constitute a single calibrated sample.

The flux density monitoring data from Ceduna are known to suffer variations that are systematic in nature and predominantly diurnal in timescale, being related to changes in air temperature at the observatory. These errors scale with source flux density and affect source and calibrator equally (as they are approximately the same brightness). The amplitude of this systematic effect for the present case is 3%, a factor of ~ 40 times smaller than the variability in AO 0235+164 discussed here. The calibrator data shown in Figure 1 demonstrates that this effect is negligible. Moreover, the variations occur on a much longer timescale than the diurnal systematic errors.

Figure 1 demonstrates that the source exhibited variations on timescales of days and months to years during the period 2003 to 2005. During the five day interval beginning 2005 July 20 the source exhibited a rapid, short timescale, increase in flux density from 1 to 2.3 Jy, followed by a fall to 1 Jy over the next five days. Over the following four days the flux density recovered to a value of 1.6 Jy, close to the long term mean flux density of the source (Figure 2).

This event is atypical of the variability commonly observed in this source and, indeed, all seven of the variable flat-spectrum quasars regularly observed in the COSMIC program. The

peak amplitude of the flux density excursion exceeds the underlying mean by 44% and occurs on the exceedingly short timescale of only $\sim 4\,$days. This behaviour contrasts markedly with the long-term intrinsic variability evident in this source, as shown in Figure 1. This event is a one-off in the COSMIC dataset; no similar events have been recorded in any of the other sources monitored in this program.

3. Analysis

3.1. Origin of the Event

The main clue as to the physical origin of this event lies in the fact that it contains an excursion well *below* the average source flux density. Of the possible causes of this event – scintillation of a compact component, an intrinsic flare, microlensing by stars in an intervening galaxy, or an extreme scattering event (ESE) in our Galaxy – only an ESE is capable of affecting the entire source brightness in such a way as to cause both the large positive and negative fluctuations observed.

In the month prior to the event, the lightcurve is flat, indicating that the flux density was dominated by quiescent emission originating from a region of the source which, we argue here, is too large to exhibit intrinsic variations on day timescales. If variations on a timescale of $\sim 40\,$days are to be attributed to intrinsic variability, causality requires that the emission region encompass a size no larger than $\sim 0.03\,\mathcal{D}\,(1+z)^{-1}\,$pc, where $\mathcal{D}$ is the Doppler factor associated with the motion of the emission region towards the observer. However, the absence of interstellar scintillation in this source places a lower limit on the source size which is incompatible with this limit. Specifically, the absence of ISS implies an apparent angular size of $\gtrsim 20\,\mu$as. Using cosmological parameters of $H_0 = 71$ kms$^{-1}Mpc^{-1}$, $\Omega_M = 0.27$, $\Omega_{vac} = 0.73$, the linear size of the emitting region must therefore exceed $0.16\,\mathcal{D}\,$pc. This size is not sufficiently small to allow causally-connected intrinsic variations in the source on the timescale observed.

An interstellar scintillation-based explanation is unsatisfactory for the same reason. The onset of scintillation would require the appearance of a new source component compact enough to exhibit ISS. However, since ISS can only affect the flux density of this new compact component, and not the extended quiescent emission, the lightcurve can never dip below the level of the quiescent emission.

Scattering due to the stellar wind of a nearby star along the line of sight to the source is also not a plausible explanation. We searched several Wolf-Rayet, O and B star catalogues through Vizier and found no nearby stars capable of generating bubbles of dense ionized

matter with the properties required for this event.

Microlensing by stars in the intervening galaxies at $z = 0.524$ and $z = 0.851$ is similarly unable to explain the magnitude of the flux density excursion. The $50\,\mu$as source size makes it impossible for microlensing to appreciably alter the entire source flux density because lensing only affects a region of size comparable to the Einstein radius. Even for the closer of the two systems, the Einstein radius of a star of mass m is only $\approx 1.56\,(m/M_\odot)^{1/2}\,\mu$as (assuming $H_0 = 70\,\mathrm{km\,s^{-1}Mpc^{-1}}$). Futhermore, we note that the observed dip in the source flux density during the event is at variance with the magnification profile expected from a microlensing event. A more detailed argument against the likelihood of microlensing in AO 0235+164 is presented in Kraus et al. (1999).

We are thus forced to conclude that only an event completely extrinsic to the source is capable of affecting the source's emission, which is too large to exhibit ISS and too large to be causally connected to an intrinsic flare. The most plausible explanation, therefore, is that the flux density excursion is caused by an ESE. We also note that the lightcurve exhibits the large increase followed by a subsequent sharp decrease which is characteristic of ESE events. This is consistent with the passing of the cloud across the line of sight in which the radiation is first focused on to the observer and then, as the observer passes the ESE boundary, the radiation is steered out of the line of sight into the neighbouring focusing region.

3.2. ESE Cloud Properties

The duration of the ESE places constraints on the transverse length scale of the ionising material. The absence of data prior to and following the high-amplitude variations places uncertainty on the total length of the ESE event. We argue that the event had ceased by day 947. This is supported by the 8 GHz data from Medicina (Bach et al., 2007) that agree well with the Ceduna data where they overlap and, following the period where rapid changes were observed, are consistent with the flux density having returned to the underlying slow intrinsic change. The earliest possible date for the commencement of the event is day 916. Thus the maximum likely event duration is $\Delta T = [947 - 916]$ days, while the minimum possible duration is 16 days assuming that the event is temporally symmetric about its peak, as is observed in other ESEs (e.g. Fiedler et al. (1987)).

The transverse extent of the cloud is

$$r = 0.18 \left(\frac{v}{20\,\mathrm{km\,s^{-1}}} \right) \left(\frac{\Delta T}{16\,\mathrm{days}} \right) \mathrm{AU}, \tag{1}$$

where v is the speed of the cloud transverse to the line of sight, plausibly in the range

$10 - 50\,\mathrm{km\,s^{-1}}$. Taking the uncertainties in both ΔT and v into account, the estimated linear scale of the cloud is in the range 0.09-0.90 AU.

Since the event significantly alters the entire flux density of the source, the angular extent of the ionized cloud must be comparable to or greater than the angle subtended by the core of the source. Space VLBI observations of AO 0235+156 place an upper limit on the core size at 4.8 GHz of $50\,\mu$as (Frey et al., 2000). This, combined with the favoured cloud size of 0.18 AU requires a cloud distance of less than 3.6 kpc.

The electron density of an ESE cloud must be much higher than the ambient medium. A simple estimate of the electron density is obtained by considering refraction by a cloud with a gaussian density profile:

$$n_e = n_0 \exp\left[\frac{-(r^2 + z^2)}{2R_0^2}\right],\qquad(2)$$

where n_0 is the maximum electron density, R_0 is the cloud radius, z is the distance along the line of sight, and r is the distance from the cloud center transverse to the line of sight. The bending angle, α, of the cloud must be comparable to the angular size of the source so that,

$$\Delta\theta \approx \alpha = \frac{1}{k}\frac{\partial\phi}{\partial r},\qquad(3)$$

where k is the wavenumber and ϕ is the phase delay imparted by the cloud. These assumptions lead to a relationship between n_0 and α as a function of distance, r, from the cloud center:

$$\alpha = (2\pi)^{1/2}\, n_0\, r_e \lambda\, \frac{r}{R_0} \exp\left(-\frac{r^2}{2R_0^2}\right),\qquad(4)$$

where r_e is the classical electron radius. The maximum bending angle occurs at $r = R_0$; this requires a minimum cloud electron density of $4.1 \times 10^3\,\mathrm{cm^{-3}}$, comparable to or higher than density estimates of previous ESE clouds (Fiedler et al., 1987).

The COSMIC program, to date, observed seven sources over a period of four years, during which time one ESE was detected. Our observation of a single event in 35 source years of monitoring is not inconsistent with the ESE rate inferred by Fiedler et al. (1987). This supports our interpretation of this phenomenon as an ESE.

There have been a number of recent reports of short-duration transients at high Galactic latitude (Bower et al., 2007; Niinuma et al., 2007; Matsumura et al., 2007). It is interesting to speculate whether short duration ESEs, similar to, or perhaps even more extreme than the event we have observed in AO 0235+164 could be responsible for these events. Bower et al.

(2007) used archival VLA calibration observations to investigate the presence of radio transients in a high-galactic latitude field for a period of about 20 minutes on average once every 7 days for more than 20 years. They identified 10 radio transient events where there is no persistent emission stronger than a few μJy. However, in addition to these events their data shows four cases where a source detected in the deep radio images was detected in only a single epoch 20 minute observation. Comparing the peak and mean flux densities, the amplification observed in these events is of the order of 2-5, larger than typical ESEs, but not implausibly so. These events may then be due to ESEs with similar timescales to the AO 0235+168 event (< 20 days). However, for the transients of Bower et al. (2007), and those detected in the Nasu 1.4 GHz observations (Niinuma et al., 2007; Matsumura et al., 2007) which have no detected persistent radio emission the implied amplifications are of the order of 10-100 or more and cannot plausibly explained by ESEs.

4. Conclusion

We observed a rapid 16 day timescale flux density variation in AO 0235+164 as part of the 6.7 GHz COSMIC program. The presence of a flux density excursion below the underlying mean flux density of the source is consistent with an ESE cloud passing through the line of sight.

Assuming an ESE cloud velocity of $20 \, \mathrm{km \, s^{-1}}$, we estimate the cloud to have a linear scale size ranging from $0.09 - 0.90$ AU and distance less than 3.6 kpc. We estimate the minimum electron density for the cloud to produce an ESE is 4×10^3 cm^{-3}.

The detection and characterisation of this ESE required the dense flux density monitoring of the COSMIC program. The rapidity of this ESE suggests that perhaps other rapid ESEs may be overlooked in other monitoring programs due to undersampling of the events.

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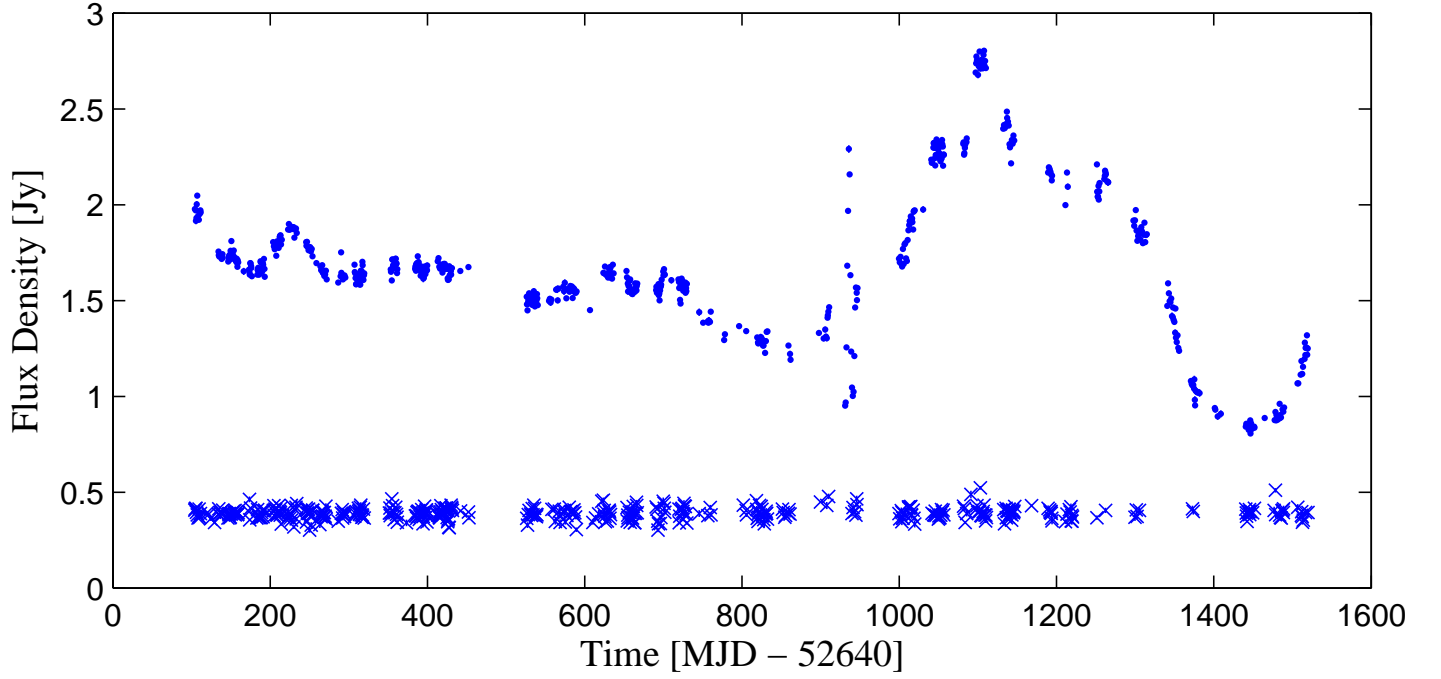Walker, M.A. & Wardle, M. 1998, ApJ, 498, L125

Fig. 1.— The 6.65 GHz lightcurve of AO 0235+164 (points) since 2003 Jan 1 (MJD 52640). The corresponding lightcurve of the calibrator, 3C 277, is shown (crosses), with 1.6 Jy subtracted from its flux densities for display purposes. The averaging time for each flux density sample is 12 hours.
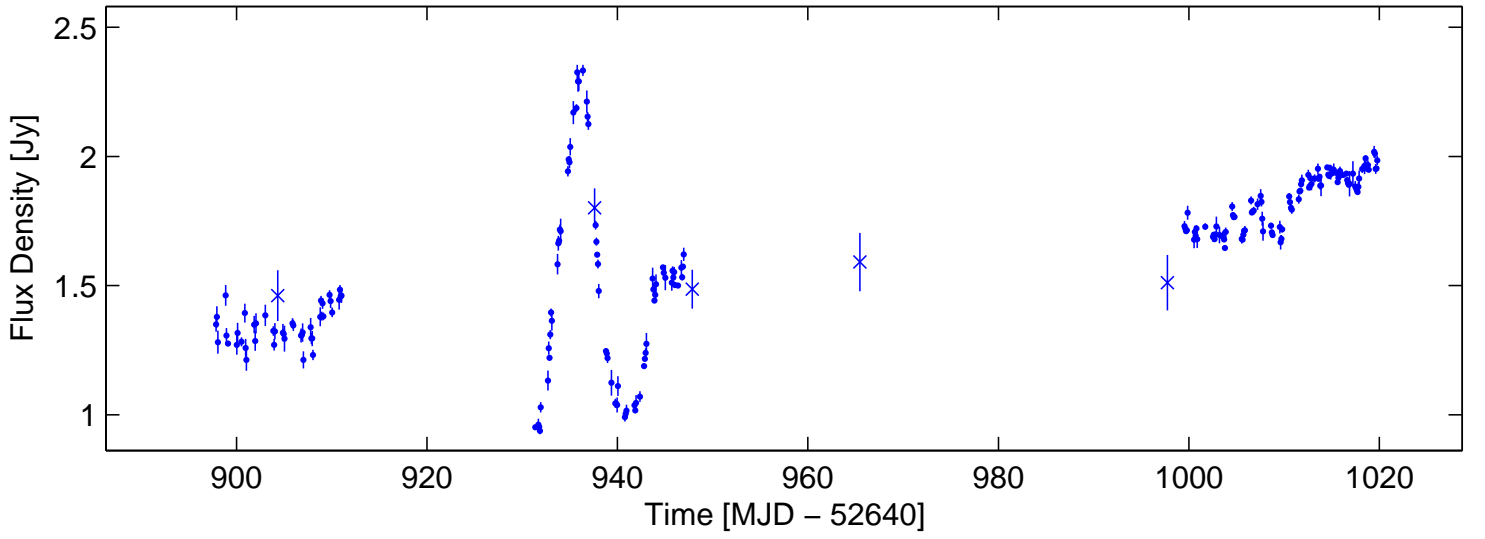
Fig. 2.— The 6.65 GHz lightcurve of AO 0235+164 during the rapid flux density variation in 2005, The averaging time for each flux density sample is 12 hours. The points marked by crosses denote 8 GHz measurements reported by Bach et al. (2007).